THE ALL ELECTRIC SHIP: ENABLING REVOLUTIONARY CHANGES IN NAVAL WARFARE

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Periodically a critical enabling technology is developed that truly revolutionizes a product. In the area of naval ship propulsion, gas turbines and nuclear power come to mind. The all electric ship including electric propulsion is such a technology as well. It represents the enabling technology for the next revolution in naval warfare. Some of the key benefits of an all electric ship include:

- Enables a revolution in warfighting capability
- Increased survivability through flexible power apportionment
- Retention of unrivaled acoustic stealth
- Superior technological growth potential
- Lower total fleet life cycle costs

A brief discussion on each of these benefits follows:

Enables Revolutionary Warfighting Capability. Current steam turbine, gas turbine and diesel propulsion systems require that a significant amount of power be dedicated to propulsion. With electric propulsion all of the available energy from the reactor plant, gas turbines or diesels is converted to electric power that can be apportioned between propulsion and other applications to best meet the ship's needs. The opportunity exists to direct the unused propulsion power for concepts such as high power weapons, sensors, and other future systems.

- Weapons
  - lasers to target and destroy enemy weapons and aircraft
  - microwave bursts to disable electronics
  - acoustic shock waves to destroy mines, torpedoes and other underwater weapons
  - electromagnetic launch for increased capacity and range
- Sensors
  - high power active sonar systems could increase detection ranges
  - high power radar systems
- Future Systems
  - improved degaussing system
  - thrusters for improved low speed maneuvering
  - multiple autonomous vehicles could be readily *recharged* in situ

Many more warfighting system concepts could probably be added to this list today. Even more would be developed in the future once programs are established to take advantage of the additional available power.

Increased Survivability Through Flexible Power Apportionment. Survivability of an all electric ship will be greatly improved by allowing power to be applied where, when, and how it is needed. The power could be applied to offensive weapons, defensive weapons and countermeasures, or put into propulsion for a fast getaway. An all-electric ship also enables a distribution architecture that can be reconfigured around damage zones and an integrated system design that can provide propulsion power from multiple sources. Finally, it provides the ability to rapidly deploy, especially for nuclear submarines and aircraft carriers, by using the diesel generators to supply power until the nuclear reactor is brought on-line. This capability could be designed into future submarines and aircraft carriers. This increased flexibility will greatly improve survivability and warfighting capability.

Retention of Unrivaled Acoustic Stealth. Acoustic stealth has always been important for submarines and is becoming increasingly more important for surface ships for several reasons:

- acoustic mines and acoustic homing torpedoes are inexpensive and readily available on the open market
- reduces detectability by the enemy
- improves surface ship and submarine detection ranges by reducing own ship noise

The all-electric ship, and in particular the electric propulsion system, enables significant improvements in acoustic stealth. The primary signature for surface ships and submarines at high speeds has always been the noise created by the propeller. Reducing the RPM of the propeller has been shown to reduce propeller noise. Unfortunately, the Navy is reaching a point where the existing gear driven propulsion systems can no longer handle the high torque associated with lower RPMs without significantly impacting the ship. Their cost, size and weight are becoming prohibitive. The recent improvements in permanent magnet motors and solid state electronics technology now offer the opportunity to achieve significantly higher torque levels in a package small and light enough to meet the most demanding Navy applications.

Superior Technology Growth. Today's electronics, weapons systems and auxiliaries rely more and more on electric power. An all electric ship would provide the basic architecture to accommodate future technology growth much more readily than a conventional mechanical drive ship. In addition, technology being developed under Navy programs such as Power Electronics Building Blocks (PEBBs), superconducting motors, and direct energy conversion could be inserted into an all electric ship.

Prospect for Lower Fleet Life Cycle Costs. Lower fleet life cycle costs are likely with an all electric ship for several reasons:

- <u>Fuel Economy.</u> A ship's fuel costs are dominated by the propulsion plant. The key to improved propulsion efficiency is the ability to operate at the maximum efficiency point for each component in the system. This is not possible with more conventional propulsion systems due to the inability to optimize efficiency over the full range of operating speeds. Electric propulsion enables each component (turbine generator, motor, motor controllers) to be loaded at its maximum efficiency point. A detailed examination of one naval ship application showed a 2 percent to 28 percent improvement in efficiency over the ship's operating profile. This improvement was achieved through specific system design features (such as modular motor and motor controller module design) and an efficient plant operating line up. As illustrated in Figure 1, using the most efficient plant operating line-up (enhanced control) results in significant improvement in efficiency below 50 percent power. The typical operational profile for Navy vessels indicates that a majority of their cruising time is at speeds below 50 percent power. The fuel cost savings associated with this efficiency improvement could be large.

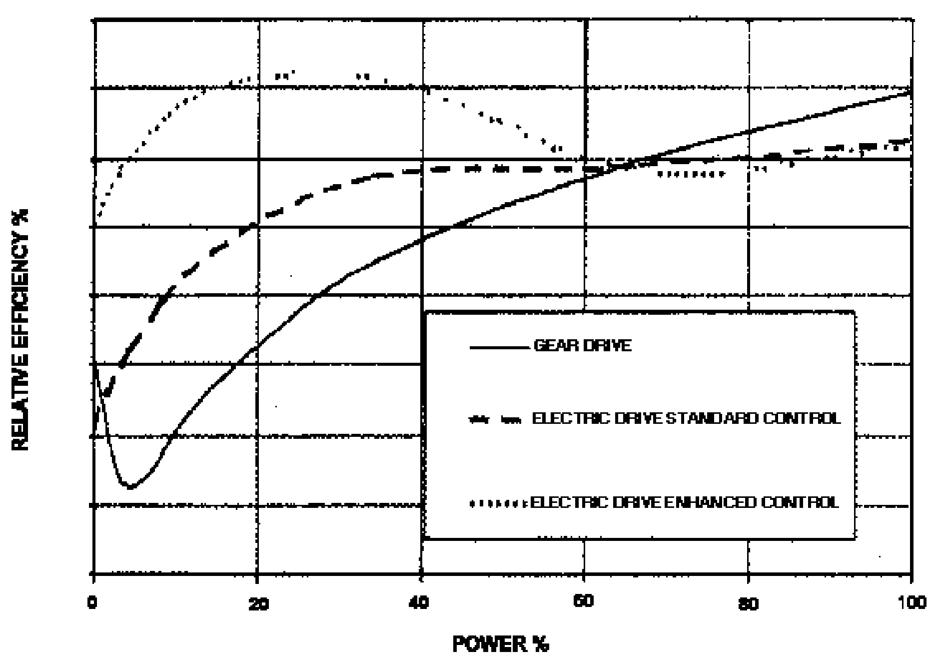

Figure 1: Relative Electric Propulsion Efficiency verses Power

- <u>Reliability and Maintainability.</u> The move to an all electric ship will reduce and in some cases eliminate the current steam, hydraulic, and high pressure air systems that tend to be high maintenance systems. In addition, one of the most avid supporters of an all electric ship has been the cruise ship industry. One reason for this support is the high reliability and low maintenance associated with an all electric ship and in particular electric drive.
- <u>Operation and Arrangement Flexibility.</u> Operationally, electric propulsion can be readily adapted to automation and monitoring. This can directly translate into reduced operating cost through reduced manning. Arrange-

ment flexibility enables ship designers to design more efficient systems. For example, future surface ship propulsion system designs, such as podded propulsion, could enable more efficient hull forms and propulsors by eliminating the shafting and related design constraints.

- Commonality. Use of common components throughout the Navy has the potential to drive the largest cost savings associated with an all electric ship. In addition to combat systems, communications, and other electronics being standardized across the Navy, the propulsion and electrical distribution systems could also be standardized. This standardization, or commonality, has the potential to significantly reduce acquisition, supply support, maintenance, and training costs. A more detailed discussion on the commonality approach is included in a later section of this paper.

To validate the lower total life cycle costs one can look at the commercial shipping industry. Cruise ships, shuttle tankers, and cable laying ships are good examples. Taking cruise ships as an example, many of the advantages discussed above are the very reason they have all gone to electric propulsion:

- Fuel Efficiency. Cruise ships spend a large amount of time at low speeds and have high non-propulsion loads, similar to Navy ships. The improved efficiency results in lower costs and higher profits.
- Reliability and Maintainability. The cruise industry only makes money when they can carry passengers. Low reliability and high maintenance are unacceptable.
- Operational and Arrangement Flexibility. Arrangement flexibility allows the ship designers to develop designs that maximize passenger capacity and overall ship efficiency. Carnival Cruise Lines recently put into service in the ELATION, which uses podded propulsion to improve efficiency and lower fuel costs.
- Commonality. The cruise industry has moved to larger classes of ships using common components to reduce acquisition, maintenance and training costs.

Electric Propulsion—Enabler for the All Electric Ship

The primary impediment to all electric ship has been the electric propulsion system. The Navy has installed electric propulsion systems on both submarines and surface ships in the past. Unfortunately, neither these systems nor the current commercial systems in use today possess the power density and acoustic quieting necessary for current or future Navy applications. Industry has, and continues to invest in permanent magnet motor and solid state electronics technology development and application. This investment has focused on both Navy and commercial applications. The result is a promising technology capable of meeting the rigorous demands of the US Navy. What remains to be done is the engineering and business analysis necessary to achieve commonality and the performance potential of each Navy platform.

Beginning in 1987, Newport News Shipbuilding (NNS), industry and the Navy embarked on studies for future electric propulsion systems and components. The results of these studies concluded that traditional motors did not offer the performance and power density required for Navy applications. Permanent magnet motors and solid state electronics offered the potential to overcome these obstacles. In 1992 Newport News Shipbuilding embarked on a program to develop and test a 3000HP permanent magnet motor. At the time it was the largest permanent magnet motor in the world. The results of this testing demonstrated that permanent magnet motors offer the performance and power density needed for Navy applications.

Electric Propulsion—Component Technology Advances

Recent advancements in permanent magnet motors and solid state electronics technology provide the technology needed for Navy applications. These advancements, driven by commercial industry, can be leveraged to reduce navy development costs.

Permanent Magnet Motors and Motor Control Modules. Permanent Magnet (PM) motors, and the solid state switching devices used to control them, are what make electric propulsion so attractive for Navy applications. They offer the Navy power density, performance, reliability, maintainability and affordability. Two market factors have brought PM motors to the forefront for propulsion applications:

(1) improvement in permanent magnet technology resulting in their widespread use by industry has significantly reduced their cost, and
(2) commercial market development of solid state power electronics equipment has significantly improved the switching frequencies and power density needed to support PM propulsion motors.

The power density of PM motors far exceeds other motor types. For example, for a given torque and horsepower and electric propulsion system incorporating PM motors could be up to five time smaller by volume than systems in use today. Figure 2 illustrates the relative sizes of PM, wound synchronous, and induction motors for a given torque and horsepower. PM motors also offer the flexibility to modify the motor and solid state controls to support quiet applications while maintaining common structural components and manufacturing methods with less quiet versions. For example, changes to magnet orientation and shape combined with improved control system algorithms and filtering of the input electrical waveform can improve the acoustic performance without affecting the basic motor and motor control module design. Reliability of PM motors is expected to be higher than other motor types. Use of permanent magnets on the rotor essentially make the rotor inert. This eliminates the types of faults that can occur on wound rotor machines.

Use of a modular design, not possible with conventional motor configurations, is the biggest advantage of the PM motor and motor control modules. Figure 3 is a completely modular design concept developed by Newport news Shipbuilding, Kaman Electromagnetics Corporation, and Northrop Grumman Marine Systems for common application across Navy platforms. Modularity enhances the ability to use components across Navy platforms. The smaller the module, or *building block*, the more likely it can be designed to meet multiple applications. Commonality across platforms could significantly reduce overall life cycle costs. In addition, a modular design incorporating removable stator modules, motor control modules and permanent magnets allows in place repair without costly hull cuts. Motor stator modules could also make the motor more fault tolerant. It is conceivable that each module is a motor in itself, a fault in one module will not significantly reduce the propulsion capability of the ship. In addition, due to the motor's sealed design it would require no scheduled maintenance (with the exception of sleeved bearings, if used) over the life of the ship. This design philosophy will significantly increase the reliability and reduce the maintainability and total life cycle cost of the system.

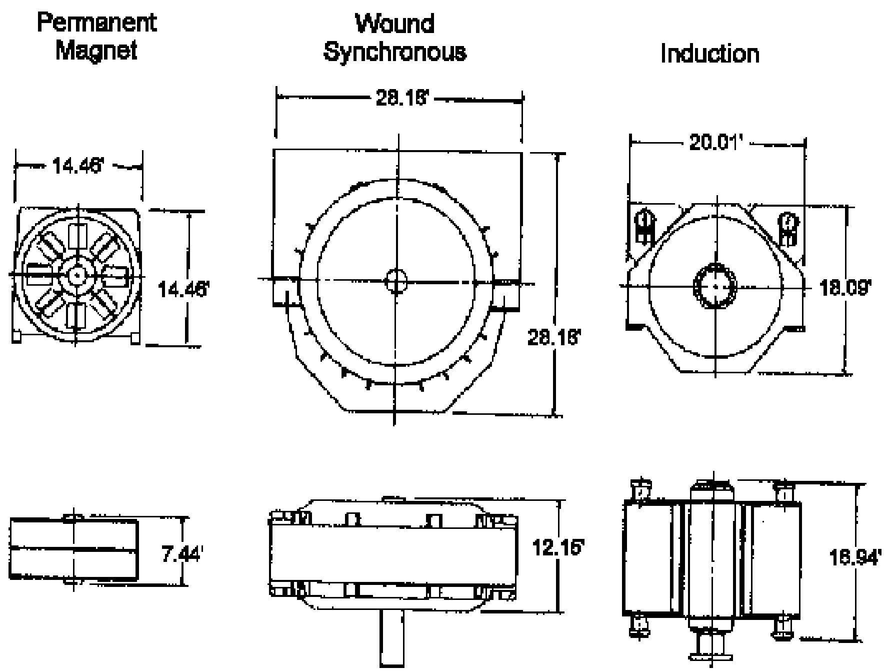

Figure 2: Propulsion Motors Sized for Comparable Torque and Horsepower

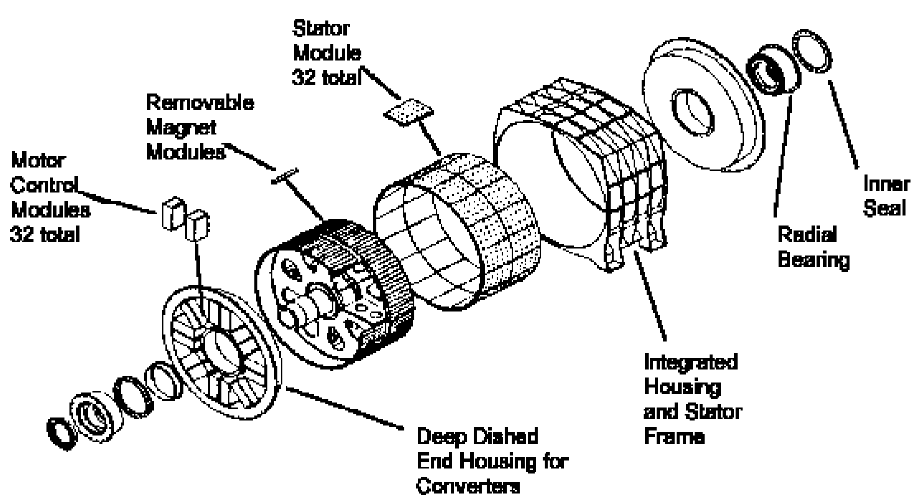

Figure 3: Modular Design Permanent Magnet Propulsion Motor

Acquisition cost is another key advantage of PM motors, especially when employing a modular design. By designing the motor with removable stator modules and magnets, the stator modules and magnets can be manufactured, assembled, and tested using the same facilities as existing commercial motors. The stators and magnets would then be assembled into the rotor and housing (existing propulsion gear manufacturers for example). All of this results in reduced labor, both in total and in specialization, which should eventually make the acquisition cost of PM motors less than any other motor type.

Electrical Distribution. The same advances in solid state electronics that went into the motor control modules also apply to the Ship Service Inverter Modules (SSIMs). SSIMs would be used in DC electrical distribution systems envisioned for future submarines, aircraft carriers, and surface ships. The SSIMs act as the intermediary between the distribution systems and components. Give a DC distribution voltage, the SSIM converts this voltage to the appropriate DC or AC input needed for each component. They also enable the use of variable speed motors, which can improve overall system efficiency and acoustics.

Electric Propulsion—Work Remaining

Permanent magnet motor and solid state electronics technology has been demonstrated. What remains to be done is the engineering to achieve the full benefits of electric propulsion. Areas such as integration, commonality, and scaling all require further engineering development. A detailed discussion of each area follows:

Integration. How the motor, motor control modules and other electric propulsion components are sized and mounted will play a big part in the ultimate cost and performance of the system. For example, achieving the acoustic performance required for submarine applications increases cost. Finding a method to achieve submarine acoustic requirements without excessive increases in component costs is critical to achieving commonality between submarines, aircraft carriers, and surface ships.

Commonality. Electric propulsion offers the unique opportunity to apply common technology and components across the fleet. One approach to achieve this commonality is to develop a family of motors based on a common motor diameter (diameter is the driving cost associated with motor design and factory tooling) and then vary the length of the motor to achieve the specific torque, RPM, and horsepower requirements of the platform. It is possible that the NSSN, DD21, and all future surface ships can utilize the commonality approach. Lower horsepower auxiliary ships may require another family of motors to cost effectively meet their powering requirements.

The costs to bring electric propulsion to the fleet will be significant. Application of common electric propulsion components allows amortization of these costs over a wider customer base. Commonality also provides a more robust and stable acquisition program, which should result in lower acquisition costs. Probably the largest cost savings will result from the use of common spare parts, training, and maintenance requirements.

Due to the differences in prime mover RPM the common component development should focus on the propulsion motor, motor control modules and ship service inverter modules. Use of common propulsion and ship service distribution equipment across the Navy fleet has the promise of significant cost savings in logistics, operation and future technology improvements.

Scaling. Tools to predict the ultimate performance (acoustic, mechanical, and electromagnetic) of electrical propulsion components and systems continue to be developed. Validation of these tools cannot be accomplished until testing at full scale is accomplished. This is another area where a modular design supports affordable development. By designing the motor stator in modules (each powered by its own motor control module) and using removable magnets it is possible to test at full scale many critical performance parameters without constructing a complete motor assembly. Demonstration of acoustic (electromagnetic source levels), mechanical (thermal performance, shock) and electromagnet (torque) performance can be accomplished prior to embarking on full-scale manufacture. This significantly reduces the risk of going full scale.

How Do We Get There?

The benefits of an all electric ship are clear. The technology hurdle associated with electric propulsion is within reach. What is needed now is the urgency, commitment and resources to ensure upcoming major acquisition programs such as DD21, future surface ships and a future NSSN can reap the benefits of an all electric ship. With adequate commitment and resources an electric propulsion system could be demonstrated and delivered with 6 to 8 years. Obtaining the resources needed to make it happen will require a clear set of goals and objectives to focus the Navy S&T, R&D, and acquisition communities. By focusing resources the advantages offered by an all electric ship can be achieved.

Summary

An all-electric ship has the potential to improve capability, reliability, expandability and affordability compared to other propulsion systems currently under consideration by the Navy. We must remember that ships being delivered today will be in the fleet for 30-50 years. It is essential they be delivered with the flexibility to adapt to the changing threats over their lifetime.

Electric propulsion is the key enabler for an all electric ship. A commonality approach will reduce development, acquisition, and total life cycle costs.

Now is the time to commit to the future. The rewards are high, the risks manageable, and all major Navy platforms can benefit.